AR-010-440

A Study of the High Strain-Rate Behaviour of GRP Composites

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DSTO-RR-0120

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Maritime Platforms Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

In this report a brief review of impact loading test methods suitable for testing composite materials is given. Results from two experimental studies undertaken to determine the dynamic behaviour of GRP composites under strain rates ranging from 40/s (low velocity) to 1000/s (high velocity) are presented. The strain rate of 40/s was achieved using a conventional dynamic tear test apparatus. A modified Hopkinson Bar was used to achieve strain rates of 1000/s and above in compression. Responses of two types of GRP composites to impact at these strain rates are compared in terms of their strength and energy absorbed capacity in fracture.

RELEASE LIMITATION

Approved for public release

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Published by

DSTO Aeronautical and Maritime Research Laboratory
PO Box 4331
Melbourne Victoria 3001 Australia

Telephone: (03) 9626 7000
Fax: (03) 9626 7999

AR-010-440
January 1998

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Executive Summary

The lack of material properties of glass reinforced plastic (GRP) composites at dynamic loading rates is holding back accurate prediction of the response of naval structures to shock loading. This study was undertaken to investigate the behaviour of glass fibre composite materials under dynamic loading and provide essential material property data as input to finite element analysis codes capable of handling dynamic loads. Materials studied were two types of generic GRP composites some components of which were similar to that used in RAN's minehunter coastal (MHC) and minehunter inshore (MHI) structural elements.

In this report a brief review of impact loading test methods suitable for testing composite materials is given. Results from two experimental studies undertaken at strain rates ranging from 40/s (low velocity) to 1000/s (high velocity) are presented, and the response of the composites at these strain rates are compared in terms of their strength and energy absorbed capacity.

The woven GRP material when tested at low strain rate showed greater capacity to absorb the incident energy with increase in its thickness. For a given incident impact energy, extensive interphase fracture occurred in thin specimens and resulted in lower absorbed energy, whereas when fracture was fibre dominated, as observed in thick specimens, the energy absorption capacity of the material was much higher. The fibre dominated fracture resulted in increased maximum strain and maximum stress when compared with interphase dominated fracture.

The compressive behaviour of composites at high strain rates showed decrease in the slopes of stress-strain curves with increase in strain rate, however, the maximum stress was not influenced by increasing strain rates. Between the two composites studied, the fillet joint material was found to have approximately half the strength of the bulkhead material.

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Contents

1. Introduction

Composite materials used in military applications are reinforced by fibres of glass, carbon and Kevlar®, giving the composites excellent mechanical properties. There is increased interest in determining the composite materials behaviour under dynamic loading because of their use in military platforms where ballistic and underwater shock impact loading are more than likely and therefore, may lead to structural damage which could reduce the residual strength and place limitations in their performance. The approach is, therefore, to study the dynamic response under impact force and relate the extent of the changes in the mechanical properties of composites to changes in the rate of strain.

In the study of material deformation behaviour under external loading a wide range of standard test methods are available in the literature published by the American Standards for Testing Materials. These methods are considerably useful for testing metallic materials under static, quasi-static and dynamic loading rates. In addition, there is now a significant understanding on the mechanical behaviour of metallic materials at high strain rates. It is now commonly known that metallic materials show elastic followed by plastic deformation behavior under quasi-static loading rates. The yield stress has been reported to increase and the plastic deformation part of the flow stress shortens when the loading rate changes from quasi-static to dynamic. Prior stress history, composition and microstructure have been shown to influence the strain rate sensitivity of metallic materials [1-3].

In the case of non-metallic materials, such as composites in particular, suitable high strain rate methods have not been standardised albeit methods suitable for testing metallic materials have been adopted. Unlike metals, composite materials have very limited ability to deform plastically, and in comparison the deformation covers a large area and is very difficult to predict [4,5]. However, the influence of strain rates on the mechanical properties of composites has been studied in various investigations [6-9]. Under these conditions, an increase in material properties was reported at higher loading rates, and sometimes contradictory results were also reported which create difficulties in making a general conclusion on the material behaviour at high strain rates. More of this material behaviour will be discussed later.

In this study, impact test methods most frequently applied to test fibre reinforced composite materials are reviewed briefly. This is followed by reporting on some preliminary experimental work carried out on glass fibre composites under impact loading using drop-weight and Hopkinson-Bar test methods.

1.1 Impact Test Methods

1.1.1 Charpy and Izod Impact Tests

Early work in the study of impact behaviour of composite materials was reported on Charpy and Izod impact test machines using notched or unnotched bend specimens [10,11]. In these types of tests strain rates of the order of 1/s are achievable using a swinging pendulum. In the Charpy method, the swinging pendulum impacts at the midspan opposite to the notch side of a beam specimen supported at its two ends. In the Izod method the pendulum impacts at the unsupported end of a vertically clamped test specimen similarly notched as in the Charpy method. Bader and Ellis [11] identified the dependence of Charpy impact energy on specimen dimensions, ie. span-to-depth ratio of the test specimen. At a span-to-depth ratio above 6 the Charpy impact energy was reported constant. Adams and Miller [12]and Adams [13] made load-time and energy-time measurements using impact bend tests with an instrumented loading tup. Both test methods are fast and useful in ranking the impact toughness of composite materials. However, Zanichelli et al [14] reported that as impact velocities increase, disturbances resulting from inertial effects get added to load/time response curves and cause inaccuracies in data analysis. Cheresh and McMicheal [15] showed the elimination of these frequency disturbances by first determining the natural frequencies of various test fixtures in the experimental set-up and then performing filtration of these frequencies from the sample response curve.

1.1.2 Drop-Weight Impact Tests

This test method is similar to that adapted in obtaining the dynamic tear energy of metallic materials. A three point bend specimen notched at mid-span is struck by a weight falling from a pre-determined height. The velocities prior to impact, during and post impact are determined using optical or photonic sensors located near the path of the falling weight and close to the specimen impact point. The energy absorbed by the specimen is calculated by using the equations of motion and impact velocity of the falling weight. Instrumenting the test specimen by attaching strain gauges is another way of obtaining dynamic strain and strain rate data. Some advantages of this test over Charpy impact test are the flexibility of using larger specimen, and variations in drop height and impactor profiles. Strain rates up to 40/s can be achieved using the drop tower method.

1.1.3 Dynamic Tests on Servo-Hydraulic Machines

Dynamic tests using servo-hydraulic machines provide greater flexibility in testing a wide variety of specimen geometries and permit the determination of a range of mechanical properties at various strain rates. In testing light-weight composite materials extreme caution should be taken to minimise inertial effects by keeping the mass of the load cell and fixture as low as possible. In these test machines strain rates up to to 100/s can be achieved.

1.1.4 Impact Hopkinson-Bar Tests

This method has been adopted to study the behaviour of various composites at impact strain rates of 1000/s. The conventional split Hopkinson bar technique was used with various modifications to determine mechanical properties under tension, compression and shear [16-18]. In a compression type Hopkinson bar, the specimen is held between two elastic loading bars one of which is impacted by the striker bar. Both loading bars are strain gauged at appropriate locations close to the specimen for the determination of the incident, reflected and transmitted stress pulse.

2. Experimental Procedures

Two experimental studies were undertaken to measure the impact resistance of GRP composites under strain rates ranging from 40/s (low velocity) to 1000/s and above (high velocity). The strain rate of 40/s was achieved using a conventional dynamic tear test apparatus comprising of a drop tower in which a mass of known weight is dropped on a three point bend specimen from a fixed height. To achieve strain rates of 1000/s and above a modified compression Hopkinson Bar was used. The following three sections outline details of the material, test methods, specimen geometries and data analysis procedure.

2.1 Material

The GRP material for notched beam specimens consisted of woven roving (WR) alternating with chopped strand mat (CSM) and an isophthalic polyester resin, Synolite 0288-T1 (47 +/- 3 wt. % resin). The directionality of the E-glass fibres in the WR was $0^{\circ}/90^{\circ}$. The number of alternate plys were **16** (consisting of **8** plys of 630 g/m^2 WR alternating with **8** plys of 300 g/m^2 CSM) and **35** (consisting of **18** plys of 630 g/m^2 WR alternating with **17** plys of 300 g/m^2 CSM) giving nominal plate thicknesses of 10 mm and 20 mm respectively. The GRP composites were generic, however the resin was that used for the MHC laminates and the reinforcement was representative of the laminated skin from the MHI sandwich structure.

The Hopkinson bar experiments were conducted on two types of composite materials. One type, designated as Pasta, was made up of chopped E-glass fibres 13 μm (dia.) x 150μm to 200μm (length) mixed with a polyester resin (60 wt. % resin) and moulded into a rod. The finished product consisted of random orientation of glass fibres in a resin matrix and some voids due to air entrapment in the mixing process. In the RAN's MHC vessels a Pasta with a vinylester resin is used as a fillet material in bulkhead-to-hull joints. The other type of material tested was woven GRP as described above for the drop tower experiments. Under impact, the loading was normal to the ply plane for woven GRP.

2.2 Low Velocity Impact

In this method the apparatus consists of a tower with vertical columns which guide a known weight of impactor to fall freely on to a notched rectangular beam specimen supported rigidly in a jig as shown in Figure 1. The striking tup profile was semi-circular and made as an integral part of the falling weight. The impact takes place at the mid-span of the notched specimen having dimensions of 182 mm x 40 mm x 19 mm and causes a three point bend loading on the specimen. The weight of the mass was 112 kg and was dropped from a height of 1.0 metre.

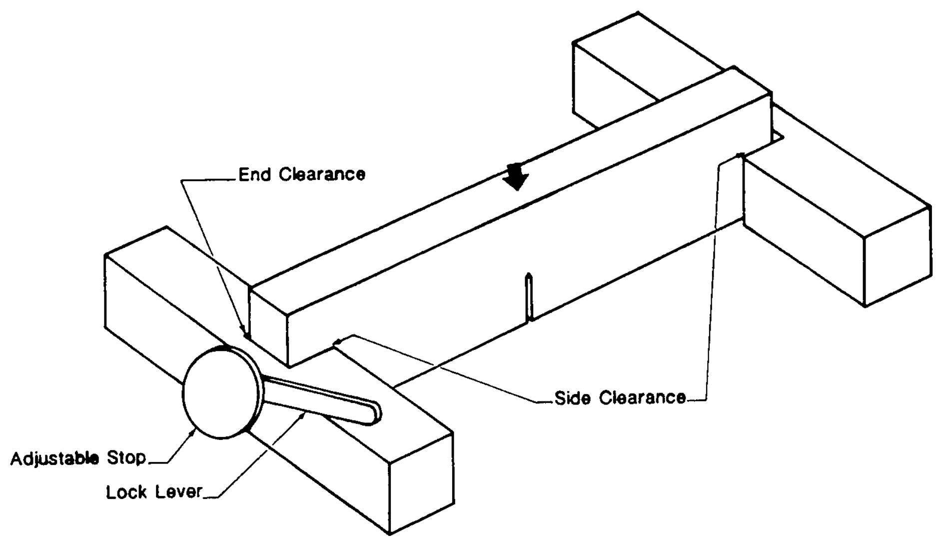

Figure 1. Specimen and location jig for low velocity testing using a drop tower.

To measure velocities prior and during impact a photo reflective sensor located close to the travel path of the falling weight was utilised. A graduated scale marker strip was adhesively attached to the falling weight so that when the fall occurs the sensing device, interfaced with a Nicolet® recorder, produces a trace of the drop-weight travel with time. A typical displacement versus time trace of the falling weight before and during impact is shown in Figure 2. In addition, Figure 3 shows the acceleration and deceleration plots of the falling weight.

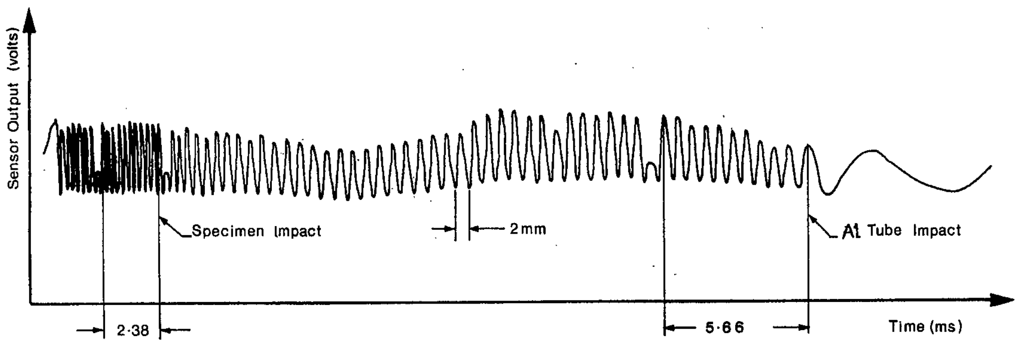

Figure 2. *A typical displacement versus time trace from a fotonic sensor used in a drop tower test.*

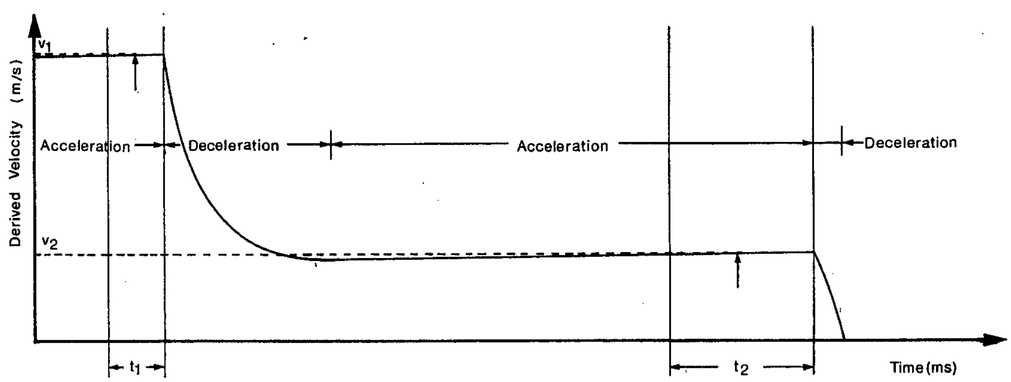

Figure 3. *A typical derived velocity versus time curve in a drop tower test.*

These traces were used to calculate impact velocity (v_1) and free fall velocity after impact (v_2). The energy absorbed by the specimen was determined in two ways; one was by using the electronic output and the other mathematical. Following the specimen impact the mass falls on aluminium solid cylinders to absorb the residual energy. The initial and post impact heights of the aluminium cylinders are used in the mathematical calculation of energy. This energy can be used as an alternative measurement and provides a back-up should the electronic method fail. The energy calculated from the electronic output is given by

$$E = \frac{1}{2} m (v_1^2 - v_2^2) + mgh$$

where m = mass of the weight
v_1 = impact velocity
v_2 = free fall velocity after impact
g = acceleration due to gravity
h = distance from top of specimen to top of the aluminium cylinders.

In the mathematical calculation of energy the following is used,

$$E = mgh^* - E_c^{\dagger} + mgh$$

where h^* = height of striker above specimen
$E_c^{\dagger}$ = energy absorbed by the aluminium cylinders

In order to measure the local strain near the specimen notch at impact, specimens were strain gauged using commercially available strip gauges with each strip consisting of five foil type strain gauge elements mounted on a common backing. Figure 4 shows the specimen and the location of adhesively bonded strip gauges which were of type N51-FA-2-120-23**. Each gauge element within the strip gauge was 2.0 mm long by 1.6 mm wide and the distance between the centre lines of each gauge was 2.5 mm. The strain gauges were connected directly into Shinkoh DAS-407® strain gauge amplifiers. The amplifiers had built-in Wheatstone bridge completion resistors and all strain gauges were connected in a quarter bridge configuration with a 2 volt bridge excitation. The analog frequency response of the amplifiers was DC 10kHz - /+1dB.

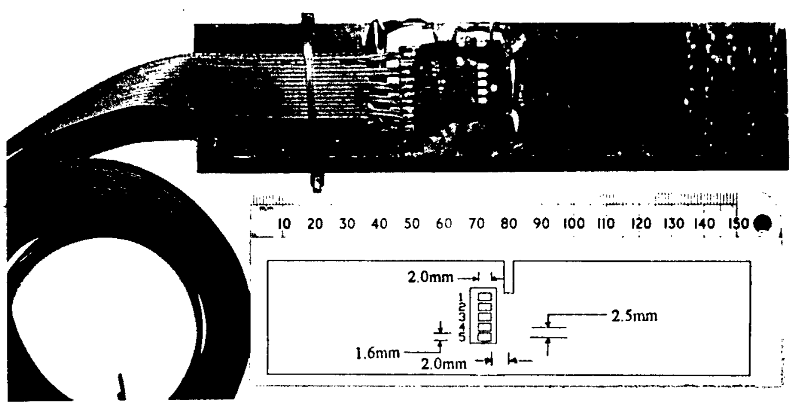

Figure 4. A three-point bend notched specimen instrumented by attaching strain gauges for low velocity impact testing.

† Estimated by dropping the impactor from different heights and measuring the initial and compressed length of Aluminium cylinders.
** Designation of Measurement Group, Inc., Raleigh, NC, USA.

The recording system consists of units each having a single channel data acquisition recorder. Each unit also contains a signal conditioning amplifier, an analog to digital converter, digital memory storage, a time clock and a serial communications port for direct connection to a PC through which the sample rate and trigger mechanism could be varied.

2.3 High Velocity Impact

The experimental set-up under this category consisted of a modified Hopkinson-Bar which allows dynamic compression loading on a test specimen. An explosive charge fired using a Ramset gun drives the impact bar towards the specimen which is held at one end of the receiver bar with teflon tape. Figure 5 illustrates 10mm by 10mm disc specimens used in the experiments. Strain gauges were attached on the receiver bar and prior to testing the strain gauge output was calibrated. The movement of the impact bar and hence its velocity prior to impact was determined from the output signal of a Fotonic Sensor. When impact takes place, strain gauges on the receiver bar produce the output of the incident and reflected impulse waves. These signals were then amplified and used to determine dynamic strain rates and stress-strain curves. Strain rates in excess of 1000/s were achieved in the current tests.

Figure 5. Cylindrical specimens for high velocity impact testing using a modified compression Hopkinson Bar.

3. Results

3.1 Strain Rates and Material Properties at Low Velocity Impact

In the dynamic tear tests, notched beam specimens of nominal thicknesses 10 and 20 mm were subjected to three point bend impact loads incident parallel to the laminar plane. From these tests the velocity of impact was measured and when averaged over several tests was found to be 4.40 m/s. The translaminar impact energies were measured in kJ. In order to discriminate the influence of the specimen thickness, the only variable in the specimen geometry, results are plotted as energy absorbed versus specimen thickness in Figure 6. More energy was absorbed as specimen thickness

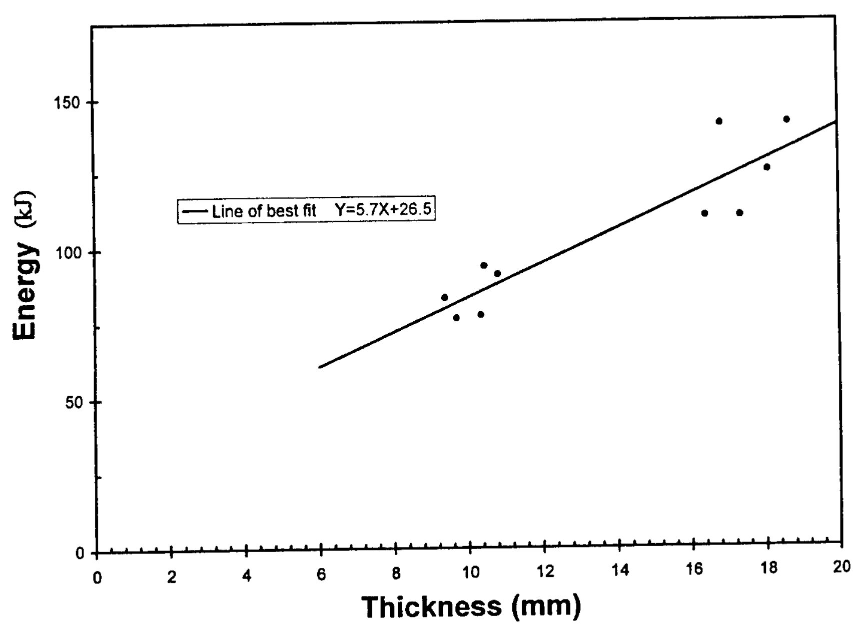

Figure 6. Effect of specimen thickness on the energy absorbed in woven GRP composite.

increased and the average difference was approximately 40%. Where the result was low fracture energy, such as found in thin specimens, the fracture occurred by extensive interphase splitting and fibre fracture. In contrast, the fracture in thicker specimens was dominated by fibre failure. These differences in fracture modes are illustrated in Figure 7.

Figure 7. The differences in fracture mode with specimen thickness. Fibre fracture dominates in thick specimens (bottom) and a combination of interphase and fibre fractures in thin specimens (top).

As an alternative, when the impact response was expressed in energy absorbed per uint thickness, results showed slightly more absorbed energy (8.3 kJ/mm) for thin specimens than for thick specimens (7.2 kJ/mm). This and the above estimation are conflicting with respect to the specimen thickness. These estimates will be discussed further in the next section.

By strain gauging test specimens, it was possible to measure surface strains and strain rates close to the notch. Results showed that for the same incident impact energy, thin specimens (9.0 - 9.5 mm) experienced higher strain rate when compared with thick specimens (15.4 - 16.7 mm). In other words, induced strain rate at impact increases with decrease in specimen thickness. In thicker specimens the maximum strains measured by the strain gauge located close to the notch ranged from 1.2% - 1.4% whereas, in a specimen of thickness 9.5 mm a maximum strain of 0.98% was measured. The calculation of maximum stresses corresponding to the measured maximum strains was carried out using a Young's modulus of 14.0 GPa typical of this type of GRP. In the specimen with a thickness of 9.5 mm, the stress calculated using the measured strain output of the strain gauge close to the notch was 138 MPa whereas, in specimens with thickness ranging from 15.4 - 16.7 mm, the calculated stress ranged from 172 to 201 MPa. Figure 8 summarises the calculated stresses for gauges 1 to 5 per specimen. The output of some strain gauges further away from the notch registered higher strains and thus resulted in higher calculated stresses than the gauges close the notch; see some scatter of results in Figure 8. This may be due to the stretching or sliding of the fibre bundles in the direction normal to the notch axis.

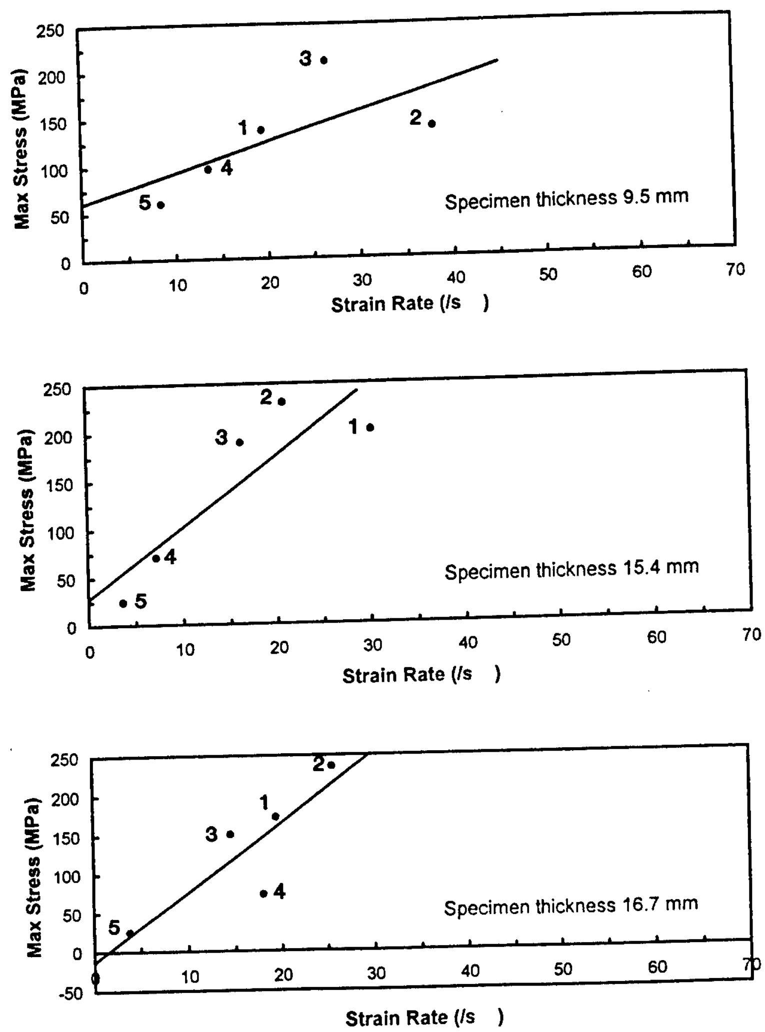

Figure 8. Calculated stresses from strain output of gauges 1 to 5 per specimen. Gauge numbers marked adjacent to data points.

In order to obtain strain rates at the notch, measured strain rates versus distance of strain gauges from the specimen notch were plotted as shown in Figure 9 (distances were measured in the notch direction).

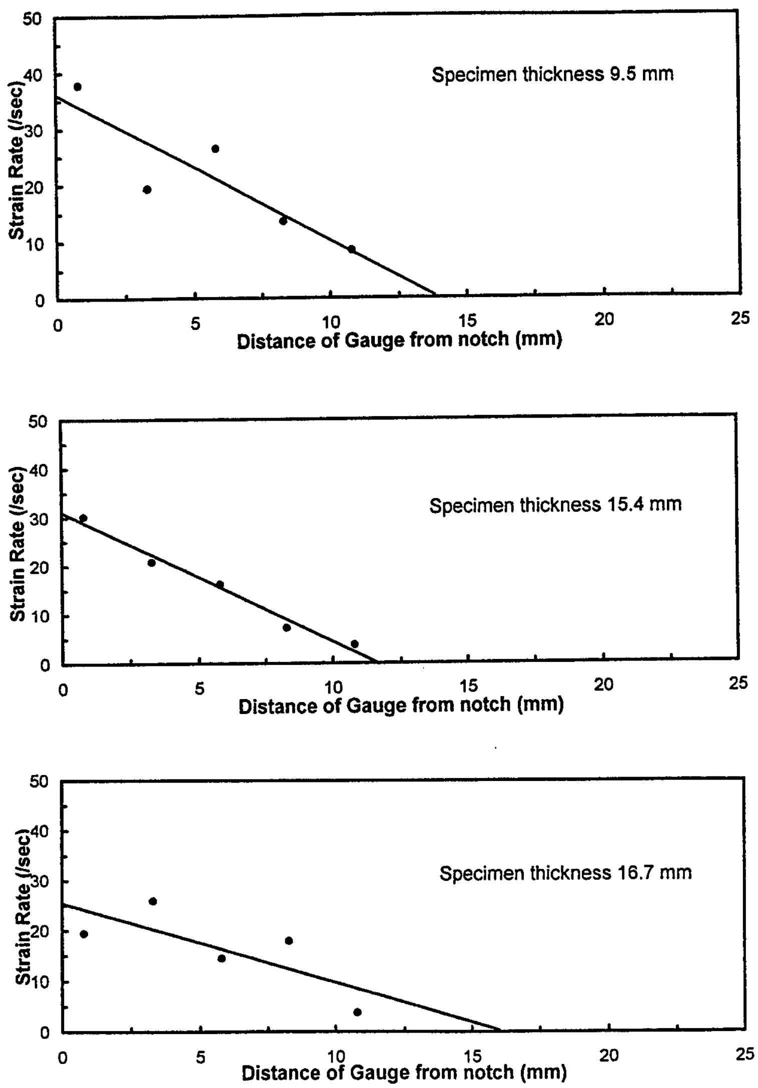

Figure 9. *Measured strain rates from gauges 1 to 5 per specimen.*

A best fit line was drawn through the data and when extrapolated to the ordinate gave an estimate of strain rate at the notch tip. In thicker specimens, these strain rates were between 25 to 32/s, whereas, in thinner specimens a strain rate of 38/s was estimated.

3.2 Strain Rates and Material Properties at High Velocity Impact

The Hopkinson Bar work was undertaken to test GRP composites under impact velocities ranging from 19 m/s to 43 m/s. In terms of strain rates the above velocities induced strain rates ranging from 1.3×10^3 /s to 4.1×10^3 /s. Compression stress-strain data was recorded along with the variation of maximum fracture strength with strain rate.

Results in Figure 10 show the influence of strain rate on the stress-strain curves for the woven GRP composite. Increasing the strain rate causes the slopes of the stress-strain curves to decrease. In addition, the maximum stress values do not differ significantly with strain rate and these ranged from 308 MPa to 345 MPa.

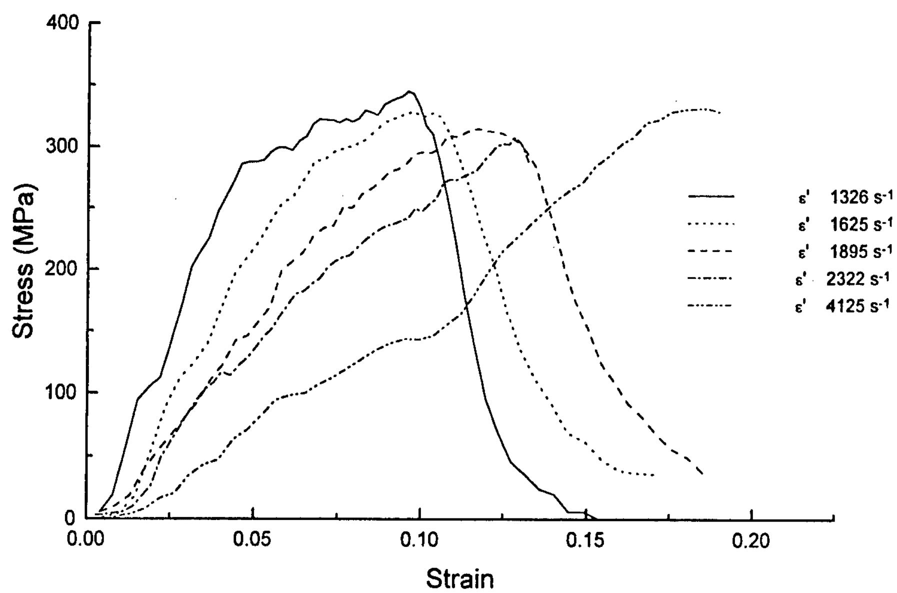

Figure 10. Stress-strain curves of GRP composite when tested in Hopkinson Bar at increasing strain rates.

Results in Figure 11 show the influence of strain rate on the stress-strain behaviour of the Pasta composite.

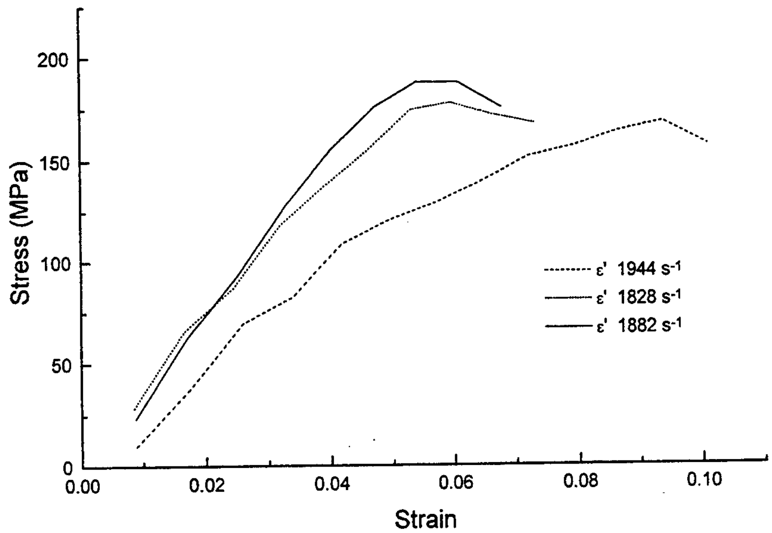

Figure 11. Stress-strain curves of Pasta composite when tested in Hopkinson Bar at different strain rates.

Even from limited tests, a trend similar to that observed for woven GRP seems to show for the Pasta, ie., increasing the strain rate results in decreasing the slope of stress-strain curves and the maximum stress values do not differ significantly with strain rates. Comparing the two composites the maximum stress reached in Pasta composite was significantly lower than that for woven GRP composite. Average values recorded were 325 MPa for GRP and 175 MPa for the Pasta. A further comparison in terms of strain corresponding to the maximum stress can be made between the two composite materials. Lower strains were measured in Pasta composite than in GRP composites. As shown in Figures 10 and 11, at strain rates ranging between 1.80 and 1.94 x 10^3 /s, strains at maximum stress were between 0.058 to 0.093 for Pasta composite, whereas, a strain of 0.115 at peak stress was measured in GRP composite at a strain rate of 1.895 x 10^3/s.

4. Discussion

Due to the lack of available data on the dynamic behaviour of glass reinforced composites of the types studied here, a comparison with the results obtained in this study is not possible. The current study has shown that under low velocity impact loading, the energy absorbing capability of GRP composite varied with specimen thickness. In thin specimens, the fracture occurred by extensive interphase splitting and fibre fracture which was in contrast to fracture by fibre failure in thick specimens. Estimates based on energy absorbed only showed thicker specimens absorbed 40 %

more energy than thin specimens. Alternatively, when estimates were carried out based on energy absorbed per unit thickness, thickness effect nearly disappeared, and results showed thin specimens to have slightly higher energy absorbtion capacity (8.3 kJ/mm) than thick specimens (7.2 kJ/mm). The fracture modes described above and illustrated in Figure 7 supports the results obtained in the first estimate. Generally, fibres play an important role as a significant load bearing constituent in a composite material. Beaument [19] reports that the primary energy absorbing mechanism in glass fibre composites is by post-debond sliding of the fibre. The fibre-dominated fracture behaviour observed in this study is an indication of greater capacity of the material to absorb the impact loading than when the fracture behaviour is interphase-dominated. It has been reported that in carbon fibre composites, low level of fibre surface treatment results in a weak interphase, and when subjected to low velocity impact in the direction transverse to the fibres, causes splitting, leaving smooth fibres on the fracture surface [20-22]. This being similar to that observed in the current study, one should therefore consider improving the fibre surface treatment to make interphases stronger in glass fibre composites particularly in thin sections.

Instrumentation of test specimens by attaching strain gauges is a useful approach in measuring strain rates and stress-strain behaviour near the point of interest, such as the specimen notch. Under a given incident impact energy, induced strain rate increased with decrease in specimen thickness. Because of the differences in fracture behaviour, the measured maximum strain and the calculated maximum stress were greater when fracture was fibre-dominated.

Harding and co-workers [16,17, 23] reported that glass fibre composites exhibit a distinct strain rate dependency in tension, ie., modulus and strength increasing with strain rate. In contrast, results reported by Armenakas and Sciammarella [9] and Daniel and Liber [24] on uni-directional (UD) glass/epoxy material showed either decrease or no influence of strain rate on ultimate stress and elastic modulus. In the current study, using a modified compression Hopkinson Bar, strain rate dependency of woven GRP and chopped glass fibre Pasta composite was observed in the form of (a) decreasing slope of the stress-strain curve with increase in strain rate and (b) maximum stress unaffected by strain rate, see Figures 10 and 11. These results may indicate that the strength was fibre dominated whereas, the path prior to reaching the maximum stress (ie. slope of the stress-strain curve and the strain to reach the maximum stress) was matrix dominated. Some evidence in support of the above proposition can be seen by examination of impacted specimens under scanning electron microscope (SEM). As shown in Figure 12, under impact the resin matrix in the woven GRP disintegrated into what looked like a powdery phase. This behaviour seems to be strain rate sensitive and therefore, may have caused the slope of the stress-strain curve to decrease with increase in strain rate. In the case of fibres, these may not be strain rate sensitive when the impact was normal to the fibres and through thickness, and therefore, caused no significant change in the ultimate strength of the woven GRP.

Figure 12. Scanning electron micrograph of a woven GRP specimen after compression failure in a Hopkinson Bar impact test.

Between the two composites investigated, very few tests were carried on the Pasta and the range of strain rate was also narrow. Therefore, it is not clear what influence the finely copped glass fibres in random orientation had on the maximum strength which showed no significant change over the range of the strain rate. However, the Pasta was found to have a lower capacity to strain and approximately half the ultimate strength when compared with woven GRP. This may be due to greater resin content and the random orientation of finely chopped glass fibres which seem not to be a strength enhancing architecture. In addition, the voids present in the Pasta, see Figure 13, may have also contributed in reducing the strength There was a tendency towards decrease in the slope of the stress-strain curve with increase in strain rate. SEM of Pasta specimens indicate the breakdown of the resin matrix into a powdery phase after impact, see Figure 13. This behaviour of the matrix was similar to that reported previously for woven GRP and may explain the observed affect on the slope of the stress-strain curves.

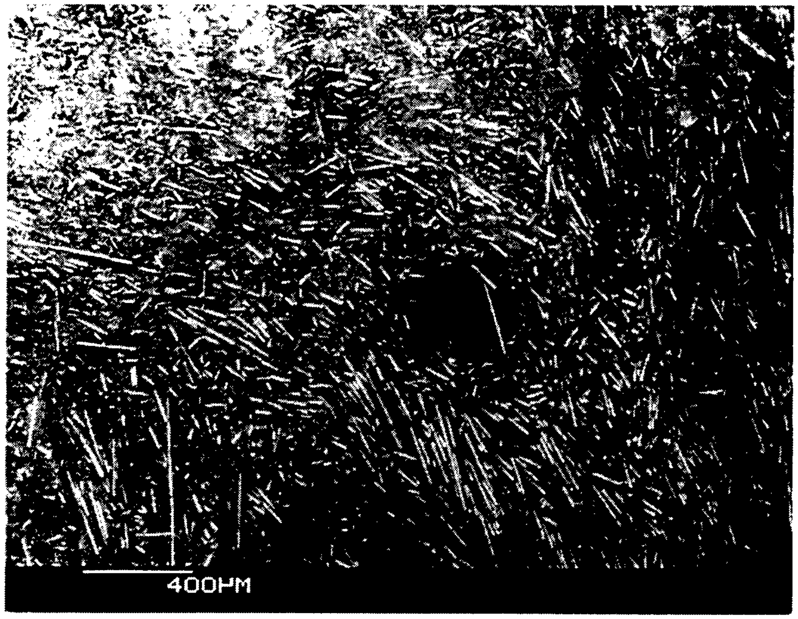

Figure 13. Scanning electron micrograph of a Pasta composite specimen after compression failure in a Hopkinson Bar impact test.

5. Future Study

The work presented in this report is the initial stage of a broader program directed at the understanding of the behaviour of naval GRP composites materials under dynamic strain rates. The poor performance of Pasta made with polyester resin is a cause of concern. A Pasta with vinyl ester resin is in use as fillet material at bulkhead-to-hull joints in the Navy's minehunter coastal vessels and therefore it is planned to study this composite over quasi-static and dynamic strain rates using a servo-hydraulic test machine and Hopkinson Bar respectively. Complete characterisation of woven GRP material properties along the $0^{\circ}/90^{\circ}$ direction under different strain rates is also planned in future investigations and these properties will then be useful as inputs in modelling of composite naval structures under dynamic loads.

6. Conclusions

A woven GRP material for minehunter bulkhead, when tested at a strain rate of 40/s in a drop tower impact, showed greater capacity to absorb the incident energy with increase in its thickness. For a given incident impact energy, extensive interphase fracture occurred in thin specimens and resulted in lower absorbed energy whereas, when fracture was fibre dominated, as observed in thick specimens, the energy absorption capacity of the material was much higher. The fibre dominated fracture resulted in increased maximum strain and maximum stress when compared with interphase dominated fracture.

The response of woven GRP and Pasta composites when tested in compression at strain rates of 1000/s and above, showed decrease in the slopes of stress-strain curves with increase in strain rate. However, the maximum stress was not influenced by increasing the strain rate. Between the two composites studied, the fillet joint composite material (Pasta) was found to have approximately half the strength of the woven GRP composite.

7. Acknowledgements

The authors would like to thank Mr. Evan Gellert and Mr. Chris Townsend for material manufacture, Mr. Nick Baldwin for assistance in drop tower testing, Dr. Steve Cimpoeru for sharing his experience with Hopkinson Bar test method and data analysis and Mr. Darren Sanford for scientific instrumentation.

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1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)

2. TITLE A Study of the High Strain-Rate Behaviour of GRP Composites	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)
4. AUTHOR(S) M.Z. Shah Khan, G. Simpson and M. Taylor	5. CORPORATE AUTHOR Aeronautical and Maritime Research Laboratory PO Box 4331 Melbourne Vic 3001 Australia

6a. DSTO NUMBER DSTO-RR-0120	6b. AR NUMBER AR-010-440	6c. TYPE OF REPORT Research Report	7. DOCUMENT DATE January 1998

8. FILE NUMBER 510/207/0828	9. TASK NUMBER NAV 94/109	10. TASK SPONSOR Task Sponsor	11. NO. OF PAGES 19	12. NO. OF REFERENCES 24

13. DOWNGRADING/DELIMITING INSTRUCTIONS None	14. RELEASE AUTHORITY Chief, Maritime Platforms Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

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16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CASUAL ANNOUNCEMENT Yes

18. DEFTEST DESCRIPTORS

strain rate, glass reinforced plastics, composite materials, impact tests, dynamic response, dynamic tests, tear tests, minehunters (ships)

19. ABSTRACT

In this report a brief review of impact loading test methods suitable for testing composite materials is given. Results from two experimental studies undertaken to determine the dynamic behaviour of GRP composites under strain rates ranging from 40/s (low velocity) to 1000/s (high velocity) are presented. The strain rate of 40/s was achieved using a conventional dynamic tear test apparatus. A modified Hopkinson Bar was used to achieve strain rates of 1000/s and above in compression. Responses of two types of GRP composites to impact at these strain rates are compared in terms of their strength and energy absorbed capacity in fracture.

RESEARCH REPORT DSTO-RR-0120 AR-010-440 JANUARY 1998

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